TUNABLE SUPERCONDUCTING RESONATORS USING FERRITE SUBSTRATES

D. E. Oates and G. F. Dionne
Lincoln Laboratory
Massachusetts Institute of Technology
244 Wood Street
Lexington, MA 02173-9108

ABSTRACT

Tunable superconducting resonators have been demonstrated using microstrip circuits of YBCO at 77 K and niobium at 4 K coupled to polycrystalline magnetic garnet substrates. At X band and 77 K, a tuning range $\Delta f/f$ of greater than 3% and Q of 2500 have been demonstrated in applied fields of 100 Oe for YBCO. The figure of merit $2Q\Delta f/f$ is 175. For niobium at 4 K a Q of 5000 has been demonstrated and a figure of merit of 288. An analytical model gives good agreement with the measurements.

INTRODUCTION

Planar superconducting bandpass filters have proven to be useful in many applications, for instance cellular telephone systems, because of the low loss and sharp skirts that are possible with superconductors while maintaining a compact geometry [1]. In many applications, however, greater utility would be gained with tunable filters. Both tunable bandpass and bandreject filters have been shown to have important applications. In addition to the low loss and sharp skirts of superconducting filters, which the tunable filters must preserve, such filters must also provide wideband tunability of 5-10% or greater and a short tuning time of 1 μs or less. Such specifications are difficult to achieve by conventional technology with size and weight comparable to that of a superconducting filter, even taking into account the necessary cooling system for the superconductors.

Previous reports of superconducting tunable filters have been primarily on the use of strontium titanate (STO) nonlinear-dielectric thin-film overlays to provide the tuning by means of the voltage-dependent dielectric constant of the STO [2]. Such devices, while providing adequate tunability range and speed, suffer from degraded performance because of the low quality factor of the STO whose tan δ is greater than 10^{-3}.

Magnetically tunable resonators fabricated from YBCO films deposited on single-crystal YIG substrates have also been reported [3]. The tunability of these devices was adequate but the performance, while encouraging was limited by the Q of the YIG sample used. Although single crystals have the potential of providing substantial advantages over other forms of ferrite substrates, particularly in applications that require frequent and rapid changes of the magnetic state, their use in magnetic components has been limited to cases for which the unique features of single crystals are necessary. Consequently, good quality crystals or epitaxial films of adequate size are not commercially available at a reasonable cost. For our present initiatives, we are using polycrystalline ferrite for the substrates. The material is readily available in sizes needed for multipole filters, is inexpensive, and supports high Q operation. In addition, the polycrystalline materials may readily be altered in chemical composition to optimize properties such as saturation magnetization and coercive field for cryogenic operation.

A figure of merit K for tunable filters has been proposed [4]. It is defined as

$$K \equiv 2\frac{\Delta f}{f}Q_U \qquad (1)$$

where Δf is the tunable bandwidth, f is the frequency of operation, and Q_U is the unloaded Q. Although originally introduced for the nonlinear dielectric devices it can be used for the ferrite devices as well. Typical K values reported for nonlinear-dielectric superconducting resonators are between 20 and 50. For the resonators described in this article the K value is nearly an order of magnitude greater, as discussed in the following.

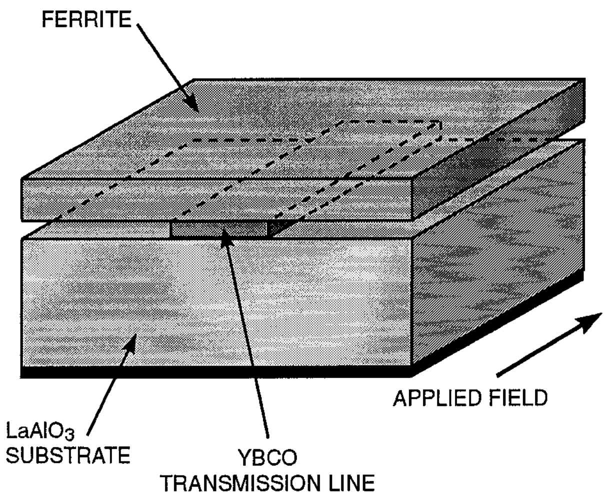

Figure 1: Schematic view of YBCO/Ferrite tunable resonator. The YBCO microstrip is fabricated on a $LaAlO_3$ substrate and clamped to a ferrite slab for tunability. The magnetic field is applied in the plane of the ferrite and parallel to the microstrip.

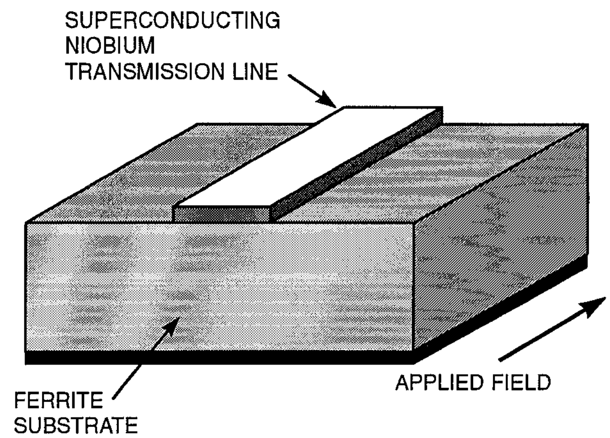

Figure 2: Schematic view of the niobium-on-ferrite microstrip resonator. The niobium is deposited directly on the ferrite. The magnetic field is applied in the plane of the ferrite and parallel to the microstrip.

EXPERIMENTAL DEVICES

We report here the first experiments to obtain wide tunability and high Q using superconducting resonators coupled to polycrystalline garnet ferrite substrates (Trans Tech G1210). We have exploited the magnetic-field-dependent permeability $\mu(H)$ of the ferrite. These substrates have low loss at microwave frequencies, and we have previously demonstrated [5] that, by preventing penetration of the superconductor by the dc magnetic flux in the ferrite, ferrite/superconductor devices can preserve the low losses of superconductors yet allow interaction of the rf fields with the ferrite.

In this work, two different devices were studied. The first is a YBCO microstrip on $LaAlO_3$ that is clamped to the polycrystalline ferrite substrate. The YBCO was deposited on both sides of the $LaAlO_3$ and includes a ground plane. Figure 1 shows the YBCO resonator. This arrangement is necessary because at the present time it is not possible to deposit YBCO directly on to polycrystalline ferrite. To obtain the ordered growth required for good superconducting properties it must be grown epitaxially on a lattice matched substrate such as $LaAlO_3$. Placing the ferrite in intimate contact with the YBCO stripline allows the strong interaction of the rf magnetic fields of the superconductor with the magnetization of the ferrite and thus allows sufficient tuning.

The second device reported here is fabricated from superconducting niobium deposited directly on the ferrite substrate including a ground plane. Figure 2 shows the niobium-on-ferrite resonator. Superconducting thin-film niobium can be successfully deposited on polycrystalline ferrite by sputtering. The niobium requires testing at 4 K but the circuit is easy to fabricate and convenient to analyze because there is only one substrate involved. In addition the simple structure minimizes parasitic effects so that the experiments can test the inherent limitations of the ferrite.

For both devices we employed a planar microstrip geometry with a $n\lambda/2$ resonator whose characteristic impedance is approximately 50 Ω (width = 230 μm, substrate thickness = 380 μm for the niobium-on-ferrite devices.) Capacitive coupling gaps at the ends of the line provide weak coupling so that we could accurately determine the unloaded Q. An external magnetic field was applied in the plane of the substrate and parallel to the propagation direction of the microstrip. Several devices have been fabricated with different resonance frequencies.

EXPERIMENTAL RESULTS

Figure 3 shows results of measurements of the Q and resonance frequency of one of the YBCO resonators as a function of the applied magnetic field. These results are at 77 K. This device showed a Q of approximately 2500 and a tunability

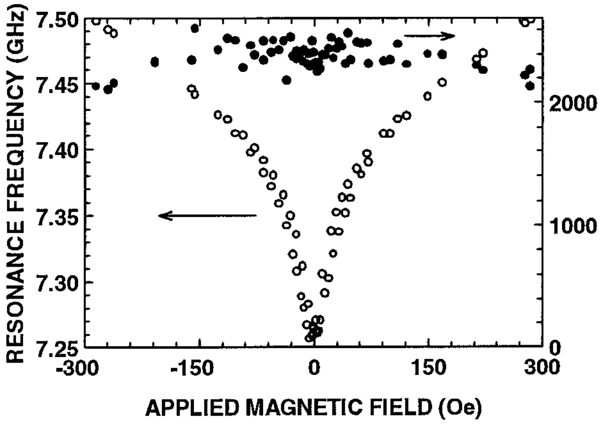

Figure 3: Plot of f_0 (open circles, left scale) and Q (closed circles, right scale) vs. applied field for a YBCO microstrip resonator on a $LaAlO_3$ substrate coupled to polycrystalline iron garnet.

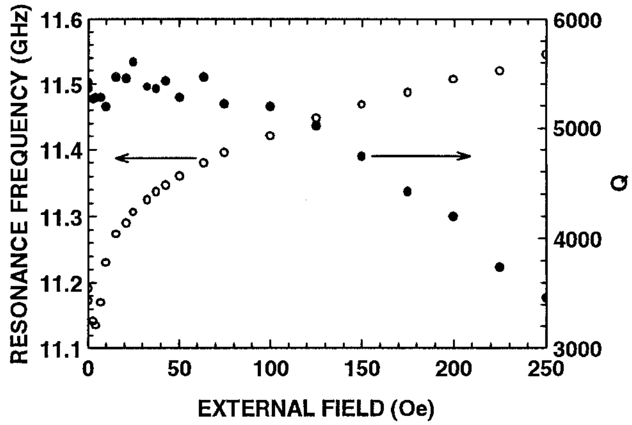

Figure 4: Plot of f_0 (open circles, left scale) and Q (closed circles, right scale) vs. applied field for a niobium microstrip resonator on a polycrystalline iron garnet substrate.

of 3% for applied fields of approximately 100 Oe. This is a very small tuning field and can easily be obtained with a relatively small coil. The field was applied in the plane of the substrate by an external coil and parallel to the propagation direction. Most of the tuning takes place at very low fields indicating that the magnetization of the substrate is responsible for the effect. The figure of merit (Eq. 1) for this resonator is 172. We believe that the Q and thus the figure of merit are being determined by the Q of the ferrite. We have measured separately the Q of the YBCO resonator at 77 K. At 7.7 GHz the Q was 5800 without ferrite. Thus we conclude that the either ferrite losses or the parasitic losses of the clamped structure are limiting the Q.

Figure 4 shows the Q and f_0 for a niobium resonator on ferrite. This device showed a Q of 5000 and a tunability of 3%. The figure of merit is 288. This Q and figure of merit are limited by the ferrite. This same resonator for instance shows a Q of 10 000 for a resonance mode at 18.8 GHz. The niobium Q decreases proportional to $1/f$ so this is the indication that the ferrite is limiting. The Q is limited by the ferrite at 11 GHz because it is close enough to the ferrimagnetic resonance frequency that losses are evident. It is interesting to note that the figure of merit is about the same at 11 GHz and 18.8 GHz because as the Q goes up the tunability goes down in proportion.

ANALYSIS

Figure 5 shows the resonance frequency vs applied magnetic field from a longer sample with lower frequency than that of Fig. 4 and measured with finer resolution. The tunability range in this case is 6% for fields below 100 Oe. This device also shows hysteresis around zero field indicating the magnetization of the substrate is having an important influence on the resonance frequency. Most of the tuning occurs at low field, just above the coercive field of the ferrite where the magnetization is changing rapidly with the magnetic field. The data of Fig. 5 show an excellent fit to a curve calculated from a new analytical model [6] that treats the partially magnetized state of the ferrite, and takes into consideration the hysteresis loop and the demagnetizing effects of the microstrip geometry. The effective permeability of the microstrip on the ferrite configuration is determined to be,

$$\mu_{eff} = 1 + \left\{ \frac{(\gamma 4\pi M)\gamma\left[H + \left(N_y - N_z\right)4\pi M\right]}{f_r^2 - f^2} \right\}$$

where f is the signal frequency and f_r is the ferrimagnetic resonance frequency. γ is the gyromagnetic factor = 2.8 MHz/Oe, H is the applied magnetic field, $4\pi M$ is the magnetization of the ferrite, N_z is the geometric demagnetizing factor in plane along the direction of propagation, and N_y is the effective demagnetizing factor of the rf magnetization component normal to the plane. In

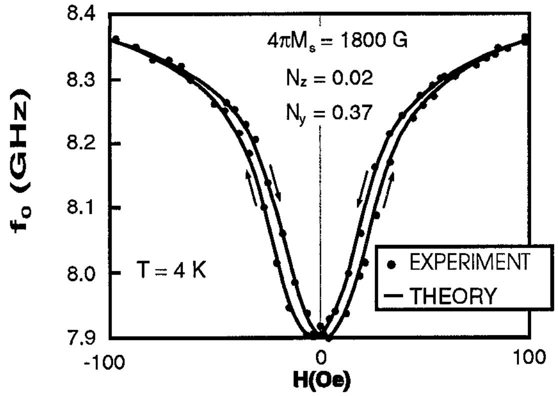

Figure 5: Plot of f_0 vs. applied field for a niobium microstrip resonator on a polycrystalline iron garnet substrate. Points are measured data and the solid line is the model discussed in the text.

these experiments the $f_r \ll f$ and H is small compared with $4\pi M$. For the stripline geometry we can approximate $N_y \approx 0.37$ and $N_z \approx 0.02$ so the final result to be compared with the experiments is

$$\frac{f(H)}{f(0)} = 1 + \frac{1}{2}\frac{\gamma 4\pi M \gamma\left(H + (N_y - N_z)4\pi M\right)}{f^2}$$

where $M = M(H)$ is a function of H governed by the hysteresis loop of the ferrite. This is the expression that is plotted as the solid line in Fig. 5 and compared with experiment. As can be seen the agreement is excellent.

Since most of the tunability that we observe results from changes in the magnetization, a practical tuning circuit need only supply magnetic fields of the order of the coercive fields of the ferrites which are usually less than about 10 Oe. Such fields can be achieved with simple magnetic structures and therefore can be made consistent with short time constants needed for fast tunability. It is also possible to provide the necessary tunability by the remanent magnetization of the ferrite in a closed magnetic circuit, thus eliminating the need to maintain a steady-state magnetic field and requiring only pulsed operation of the applied field to change the magnetization of the substrate. Well-known flux-drive techniques [7] can be used to provide continuous accurate tuning over the tunable frequency range.

SUMMARY

In summary, we have demonstrated resonators with wide tunability and high Q by using superconductors on ferrite substrates. The tunability occurs at low magnetic fields so that a very simple coil can provide the necessary field, and time constants can be kept low so that rapid tuning is possible. This demonstration provides great promise for tunable multipole filters in compact form at microwave frequencies.

ACKNOWLEDGMENTS

This work was supported by the Department of the Air Force and the Defense Advanced Research Projects Agency. We also thank the Innovative Research Committee at Lincoln Laboratory for support. We thank Alfredo Anderson for supplying the YBCO. We thank R. P. Konieczka for invaluable technical support. We also thank J. A. Weiss for numerous technical discussions.

REFERENCES

[1]. G.-C. Liang, D. Zhang, C.-F. Shih, M. E. Johansson, R. S. Withers, W. Ruby, D. E. Oates, A. C. Anderson, P. A. Polakos, P. M. Mankiewich, E. DeObaldia, and R. E. Miller "High-Power HTS Microstrip Filters for Wireless Communication," *IEEE Trans. Microwave Theory Tech.*, vol. 43, 3020-3029 (1995).

[2]. D. Galt, J. C. Price, J. A. Beall, and R. H. Ono, "Characterization of a Tunable Thin Film Microwave $YBa_2Cu_3O_{7-x}/SrTiO_3$ Coplanar Capacitor," *Appl. Phys. Lett.*, vol. 63, pp. 3078-3080, 1993.

[3]. D. E. Oates, A. Piqué, K. S. Harshavardhan, J. Moses, F. Yang, and G. F. Dionne, "Tunable YBCO Resonators on YIG Substrates," *IEEE Trans. Appl. Superconduct.*, 1997 (in press).

[4]. O. G. Vendik, L. T. Ter-Martirosyan, A. I. Dedyk, S. F. Karmanenko, and R. A. Chakalov, "High-T_C Superconductivity: New Applications of Ferroelectrics at Microwave Frequencies," *Ferroelectrics*, vol. 144, pp. 33-43, 1993.

[5]. G. F. Dionne, D. E. Oates, D. H. Temme and J. A. Weiss, "Ferrite/Superconductor Devices for Advanced Microwave Applications," *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 1361-1368, 1996.

[6]. G. F. Dionne and D. E. Oates, "Frequency Tunable Microstrip Ferrite Resonator in the Partially Magnetized State," Digest of the 1997 International Magnetics Conference (Intermag 97) April 1997, paper BD-04; to be published in *IEEE Trans. Magn.* (1997).

[7]. W. J. Ince and D. H. Temme, "Phasers and Time Delay Elements," *Adv. Microwaves,* vol. 4, pp. 1-189, 1969.